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RAINFALL-RUNOFF ANALYSIS FOR ESTIMATING EFFECTS OF CLOUD SEEDING ON WATER RESOURCES IN GALILEE, ISRAEL

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1. INTRODUCTION

Cloud seeding has been carried out in Israel to enhance precipitation for the last 24 years. Activities have comprised two short randomized experiments as well as operational seeding. Since 1969 seeding has focused mostly over northern Israel, where the second experiment was conducted during six rainfall seasons 1969/70-1974/75 (Gagin and Neumann, 1981), followed by full operational seeding which continues to the present. AgI-NaI particles are dispensed from aircrafts flying along a north-south line, and from ground generators located in the downwind target area. The coastal plain west of the seeding line serves as a control area. Statistical analysis of the second experiment indicated a 13% overall increase of rainfall at a 0.028 level of significance. Results were also reported for target sub-areas.

In order to assess the extent to which cloud seeding is actually augmenting the country's water resources potential, a hydrologic study has been initiated to identify changes in the flow of streams (surface runoff) and springs (underground runoff) draining the catchment basins within the target area.

Previous studies of hydrological effects of weather modification are few. Some compare streamflows in seeded areas and in control areas (e.g., Henderson, 1981), while others simulate the transformations of induced rainfall to runoff (e.g., Lumb and Linsley, 1971; Negev et al., 1971). The results indicate that in temperate and semi-arid climates (as of northern Israel), the relative increase in runoff is considerably larger than the relative increase in rainfall over the catchment basin, a phenomenon that gave rise to our hopes for detecting flow changes by observational statistical methods.

To analyze the effect of past cloud seeding on water yields, we had to rely on historical comparisons of the runoff-rainfall relations in seeded and unseeded years. Also, compensation had to be made for man-made changes in the catchment basins during the relevant periods.

To deal with these problems we have developed a double regression approach (rainfall/runoff-target/control) that makes use of flow measurements as well as rainfall data from target and control areas.

2. DATA

The Galilee target area extends over some 2,000 km^2 between the Mediterranean coast to the west, the Hula and Kinneret Valleys to the east, the Lebanese border to the north, and the Yezre'el Valley to the south. The terrain is mostly rugged to mountainous. Natural drainage - surface and groundwater - flows west into the Mediterranean or east to the Jordan. The control area - the coastal plain to the west of the target area - is 80 km long and less than 10 km wide in the north, widening out towards the south. For the purposes of this study, the target area (N) and control area (A) have been further subdivided into smaller zones on the basis of orography, climate, or to correspond with specific catchment basins (Fig. 1).

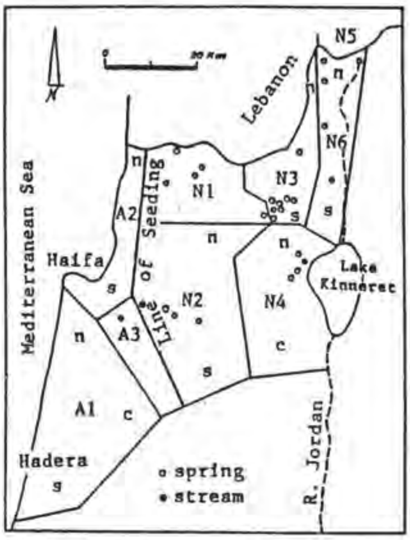

Fig. 1: Location of Galilee target areas (N), control areas (A), and spring and stream gauges.

The rainy season extends from November to March with an average rainfall in Galilee of over 600 mm per year. Winds on rainy days are predominantly westerly. Records of annual rainfall from 98 Meteorological Service stations were compiled by hydrological year and classified by zone. Index rainfall series for each one were computed from the means of all the stations within the zone. Two time periods were defined: (1) the pre-seeding period, prior to 1959/60 (in some cases to the late 1920s); and (2) the seeded period, 1969/70-1981/82. (The intermediate years were excluded because of the absence of a control area.) The latter 13-year period comprises the second experiment (6 years) and the susbsequent operational seeding (7 years).

Annual flow data from 4 streams and 22 springs were obtained from the Hydrological Service. Although the catchment basins of the springs could not be defined with precision there is evidence that except in two cases the catchment basins lies entirely within the limits of the target area. Mean flow ranges from 0.1 million cubic meters per year (MCM/yr) to 21.9 MCM/yr. Most of these sources cease to flow in the dry season.

In cases where the runoff response to rain was not confined to a single rainy season and there was some carry-over to following years, recession-analysis adjustment was used to distinguish the contribution of the specific season's rainfall.

From the outset of data compilation it was recognized that between the unseeded and seeded periods, basins might have undergone systematic (structural) changes - such as landscape modification, diversion of flows, withdrawal of groundwater, introduction of drainage and sewage effluents, alterations in gauging stations, etc. - that should be accounted for in any runoff-accretion detection process. The data preparation aspects are discussed in Harpaz and Keller (1984). At a similarly early stage, it was decided to exclude control areas A2 and A3 because of suspicious "contamination" effects during seeding (Harpaz, 1985). Only area A1 therefore remains for further analysis (preseeding rainfall correlation coefficients with target zones are in the range of 0.74-0.93).

3. STATISTICAL ANALYSIS

The statistical analysis of rainfall-runoff relationships in target and control areas attempts to identify those interperiod changes that are clearly related to cloud seeding, as distinct from other systematic changes.

Let x_t denote the rainfall in the control area in the t-th season, and let y_t be the rainfall in the target area in the same year. We assume that the relationship between x_t and y_t is linear, and that in seeded years there is an additive effect of cloud seeding on target rainfall.

Let w_t denote the runoff in the target area at the t-th season. It is assumed that a linear relationship holds between some concave transformation of w_t and the rainfall in that area. Let $z_t = f(w_t)$ be the transformed runoff (for which we shall still use the term runoff). The combination of these assumptions yields the following relation between target runoff and control rainfall

$$z_t = \alpha_1 + \beta_2\delta_t + \alpha_3 x_t + u_t \qquad (1)$$

where δ_t takes the value 1 in seeded years and 0 otherwise, and u_t is an independent error term.

This first-stage model implies the following estimation procedure: Regress runoff on rainfall on target in seeded years and unseeded years, constraining the two regressions to have the same slope. The difference in the estimated intercepts $\hat{\beta}_2$, estimates β_2 which measures the increase in runoff due to seeding. An example of these two regressions for a water source, before they were constrained to have the same slope, is given in Fig. 2(a).

Because the unseeded period and the seeded period are on the average twenty years apart, the model allows for structural changes in the target area which might affect the relationship between runoff and target rainfall in a way which is not related to seeding. We assume, for sake of simplicity, that the effect of the changes is additive, thus yielding the model

$$z_t = \gamma_1 + \gamma_2\delta_t + \gamma_3 y_t + v_t \qquad (2)$$

where v_t is an independent error term. Again, (2) means that the difference due to structural changes can be estimated by taking the difference of the intercepts of the regressions of runoff on rainfall over the target area in seeded and unseeded years. An example of the two regressions, before they were constrained to have the same slope, is given in Fig. 2(b).

Combining (1) and (2) we obtain the relation between the rainfall in the control area and the run off in the target area:

$$z_t = \alpha_1 + \alpha_2\delta_t + \alpha_3 x_t + \varepsilon_t \qquad (3)$$

where ε_t is a combined error term. From (3) we see that the relation between runoff and control rainfall remains unchanged, and that the parameter α_2 measures the change in runoff between seeded years and unseeded years, after accounting for control rainfall. But in this second-stage model, it captures both the effect of seeding and that of structural changes. The net increase due to seeding, correcting for the structural changes, is

$$\Delta = \alpha_2 - \gamma_2 \qquad (4)$$

and is estimated by the difference of the two intercept differences. We use ordinary least squares estimators for the parameters in (4) to get $\hat{\Delta}$.

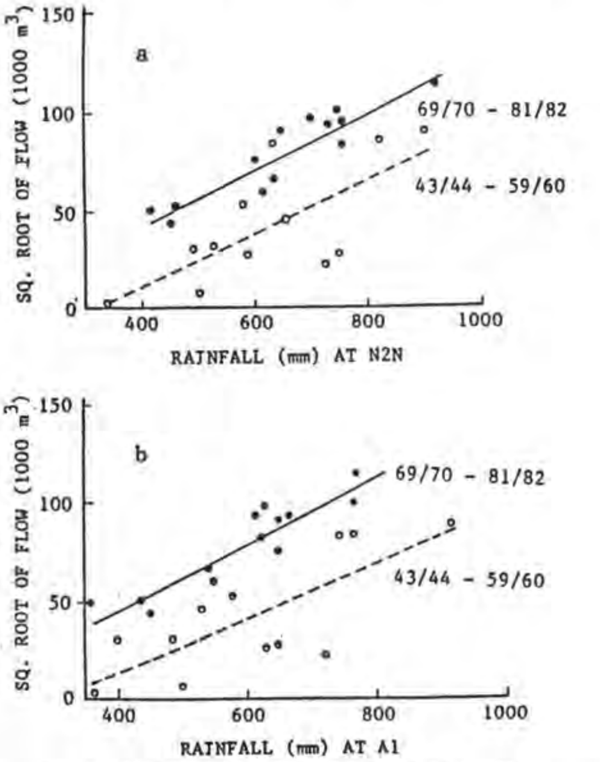

Fig. 2: Runoff in Zipori Stream vs. rainfall over its catchment basin (target zone N2N) and over control zone A1.

Although $\hat{\Delta}$ is the difference of two linear estimators, we cannot proceed with the estimation of its standard deviation in the usual way because such a procedure uses the assumption that the rainfall values are constant (or conditioned on their observed values). Such an approach eliminates an important source of variability - the relation between rainfall on control and rainfall on target. We thus turned to the Jackknife method (Miller, 1974) which estimates the standard deviation SD ($\hat{\Delta}$) by repeating the analysis leaving out one year at a time. Furthermore, $(\hat{\Delta} - \Delta)/SD(\hat{\Delta})$ has a distribution approximating student's t. This approximation was used to calculate the one-tail significance level. These absolute estimates were then transformed to relative increases by dividing each estimate by the average flow from the appropriate source in the unseeded years.

4. RESULTS AND DISCUSSION

The parameter of runoff increase in the 13-year seeded period was estimated for each of the 26 water sources. The estimated relative increases together with their standard deviations are presented in Fig. 3. They range from -6.6% to +18.7%, and in the central half from +1.8% to +10%. These increases are not very significant since the one-sided significance levels range from 0.70 to 0.04, and from 0.37 to 0.15 in the central half. Only one increase is significant at the 0.05 level, and five at the 0.10 level.

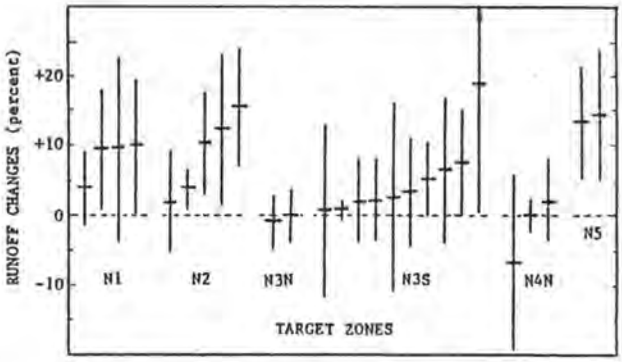

Fig. 3: Estimated runoff changes according to target zones, ± standard deviation.

Fig. 3 suggests that there may be a geographical pattern to the results. This is not surprising: first, zones were defined on the basis of similarity in orographic and hydrologic properties; second, the analyses within the same zone are highly correlated because they are based on rain data which are themselves highly correlated. Water sources on the western slopes of the Galilee hills (zones N1 and N2) indicate better response to seeding, that is, a median runoff increase in each of 9.4%, with a significance level of about 0.20 in N1 and 0.10 in N2. The eastern watersheds (zones N3 and N4) show only a 3% increase in median runoff, with significance levels of about 0.30. The two northernmost springs indicate an increase of 14% at the 0.06 significance level.

On the question of whether cloud seeding has a positive effect on runoff, the answer is mixed. Runoff increments were noticed in 24 of the 26 sources, and viewing the results of each source as independent this would constitute very strong evidence against the hypothesis that seeding has no effect on runoff. But this assumption of independence is far from true; a more realistic approach would be to regard the summaries of the zones as independent pieces of information. Using this approach, only a weak indication of increase is obtained.

The runoff responses to the reported rain increases were lower than those expected on the basis of the known rainfall -runoff relationships and those established by simulation studies. Such high changes seem very unlikely since power calculations indicate that even with the noise present in the data, an increase of 25% or more would have been detected as significant with a probability of 0.90. We are therefore of the impression that the hydrologic impact of cloud seeding may largely depend on the modification of the induced rainfall distribution.

The analysis presented here, complex as it may seem, has proved useful in detecting runoff changes during the seeding period. However, it is still based on historical comparisons. The double regression method has coped with the problems of structural changes but other biases, such as climatic change, may still remain. Gabriel and Petrondas (1983), who analyzed the validity of rainfall comparisons, concluded that such comparisons are acceptable with the caveat that they tend to be somewhat liberal. Preliminary analysis of unseeded rainfall between subzones within the control area and between control and target zones (Harpaz, 1985), suggests that interperiod changes were negligible. We therefore proceed cautiously with our conclusions.

5. CONCLUSIONS

The principal conclusion drawn is that there is a weak overall indication of runoff increase due to cloud seeding, although results of individual water sources are not rated adequately significant. The magnitudes of the changes vary widely but exhibit distinct geographical pattern. The median values for the six target zones range from 0% to 14%.

The double regression technique, rainfall/runoff-target/control, has proved useful in analyzing runoff changes with control for systematic changes in target areas. Runoff changes higher than 25% would have been evident had they actually occurred in the last 13 years of cloud seeding.

Future research will include an analysis of historical relationships within the investigated area, generalizations of models to include possible multiplicative effects, and a simulation study of runoff response to distributions of added rainfall.

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